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13. ABSTRACT (*Maximum 200 words*)

Completed work on this grant analyzes problems of 3-D vision, visual search, spatial mapping, planning and action, all of which utilize spatial representations to control adaptive behaviors in real time. Highlights include significant contributions towards solving the classical figure-ground problem for biological vision, the problem of self-organizing body-centered spatial representations for movement planning and spatial orientation, and the problem of carrying out fast visual search for targets among multiple distractors. New research directions include projects which have been developed to frontally attack core problems concerning how a rapidly moving agent can self-organize spatial representations, use these representations for real-time movement planning, and transform spatial movement plans into appropriate motor commands for movement control and real-time navigation. Specific projects include retinal image processing, formation of egocentric maps of object positions from optic flow, detection of moving objects from optic flow, integration of egocentric and allocentric representations for autonomous navigation, and investigation of spatial reference frames and transformations between frames for real-time flexible speech articulator control.

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September 1, 1993—August 31, 1994
(Year 2 of 3)

NEURAL MODELS OF SPATIAL ORIENTATION IN NOVEL ENVIRONMENTS

Contract AFOSR F49620-92-J-0449

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1. Designing a Self-Organizing Network that Calculates Translational Heading

Navigation requires heading perception. For a robot to maintain a constant heading, it is insufficient to simply set the wheels at a given specific angle and assume the resulting trajectory is correct. An autonomous vehicle on a side-hill, for example, may have to turn its wheels just to maintain a constant heading due to tire slippage. Visual feedback is a more reliable indicator of heading. Algorithms exist that allow explicit calculation of heading from optic flow, but none are self-organizing and each requires having explicit knowledge about the geometry of the sensor, the focal length of the optics, etc. Such parameters must be recalculated for each variety of robot and if they change over time, the robot will begin to malfunction.

This project investigates a self-organizing solution for determining heading from optic flow. Such a solution is generic, robust, and automatically adapts to a wide variety of robotic systems. A network-like solution has been developed based on the subspace algorithm introduced by Heeger and Jepson (1992). The subspace algorithm calculates the translational component of 3D motion without explicit knowledge of depth or rotational velocity. Its stability, generality, and efficiency place it among the best techniques available. Lappe and Rauschecker (1993) first noticed the potential of expressing the algorithm in terms of a neural model, but their model is not self-organizing.

Its weaknesses are:

(1) It only handles forward translations in the Y-plane;

(2) The weights need to be calculated off-line;

(3) It assumes heading direction cells in the heading map are predetermined.

This work has made the following improvements:

(1) The network is self-organizing for both the heading field and the weight field;

(2) The network determines heading for all directions in the sphere, not just 2-dimensional forward motion.

A schematic diagram of the heading network is shown in Figure 1.

2. Building a Range Map from Optic Flow Information

A second requirement for navigation is knowledge of the 3D spatial arrangement of objects in the environment. Information about the depth of objects is encoded in optic flow but somewhat difficult to extract when arbitrary motions of the observer are allowed. This project investigates how to use information from the heading network to build a range map of the visual scene.

Since two unknowns, translational velocity and inverse depth, are multiplied by each other in the optic flow equation, optic flow cannot give information about absolute speed of the navigator or absolute depth of objects. However, a self-organizing network has been developed that yields relative inverse depth information. When travelling parallel the optic axis, the relative depth information becomes equivalent to a time-to-collision measurement.

The network, shown in Figure 2, uses extraretinal information regarding eye rotational velocities and heading direction from the previously describe network to self-organize into a range map. Future work will involve placing the eye-centered range information into a body-centered representation for navigation.

3. Neural Controller for a Mobile Robot

Since the earliest stages of this project, Professor Gaudiano has been involved with the development of a neural network for the low-level control of a mobile robot. This line of work

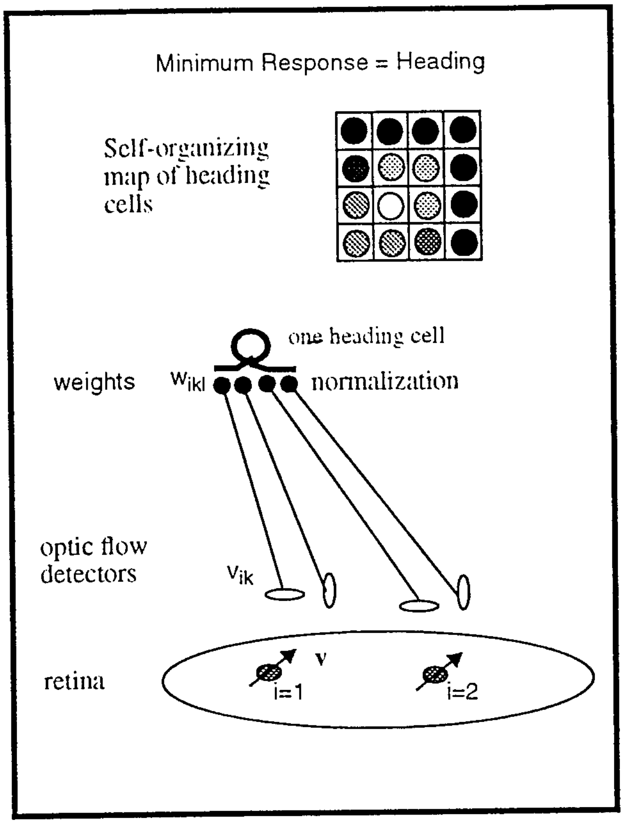

Figure 1. Self organizing network for extracting eye-centered ego-motion.

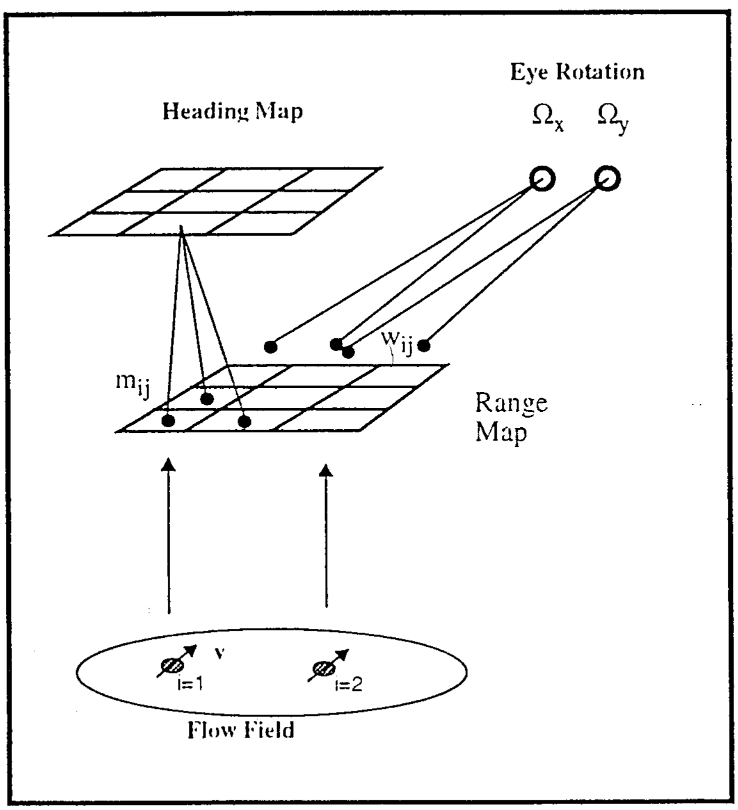

Figure 2. Self-organizing range network.

has been extended during the course of the project year, and is the subject of further research. A first manuscript describing the neural controller will appear shortly in the international journal *Neural Networks*. A second article has been accepted (pending some revisions) for publication in a special issue of the *IEEE Transactions on Systems, Man, and Cybernetics*. The latter article provides more rigorous tests and analyses of noise resistance in the neural controller; it proves asymptotic stability of the neural control scheme; and it illustrates some initial attempts to implement the neural controller using the commercially available robot *ROBUTER*. The results obtained to date demonstrate that the proposed neural controller offers a viable alternative to more traditional controllers, especially when the robot must operate in an unknown or nonstationary environment.

We have also begun formal development of a neural architecture for navigation and obstacle avoidance, to be used in conjunction with the low-level controller. The architecture, which had been sketched in an earlier progress report, combines information about target and obstacles into a spatial map. The target is represented as a positive Gaussian distribution of activity, while each obstacle is represented as a negative Gaussian. Combination of all Gaussians into a spatial map generates an activity surface similar to the functions used in so-called "potential field" approaches to navigation, which typically utilize gradient descent procedures to locate the maximum of the potential field corresponding to the given configuration of target and obstacles. Unlike potential field approaches, the approach proposed here does not make use of gradient descent: instead, the competition in the spatial map makes it possible to extract a time-varying peak whose position reflects the moment-by-moment direction that the robot must follow in order to reach the target while navigating around obstacles.

In the most recent progress report, a diagram had been included to illustrate how such a scheme might be implemented within the context of a *conditioning circuit*, a neural network model proposed by Grossberg to explain how humans and animals can learn to exhibit appropriate avoidance or approach behavior in response to a given set of external sensory cues, while also taking into account the human's (or animal's) internal needs. In that proposal, it was suggested that each item in the environment that represents an obstacle or target, is stored in memory along with its position in space. However, it was suggested that each object's position would be stored in allocentric (i.e., relative to a fixed external frame) Cartesian coordinates. We have found that a better performance is obtained by utilizing instead an egocentric polar map, in which the position of the target and obstacles are continuously updated as the robot moves in space. With this scheme we have been able to demonstrate robust obstacle avoidance in the presence of moving or stationary target and obstacles, for a variety of configurations of obstacles. We are currently extending this work to include modulation of the Gaussians as a function of internal needs, for example, as a function of the robot's need to recharge its batteries. We are developing schemes to avoid getting caught in "local minima", for instance when the robot is surrounded by obstacles, while the only possible path out of the obstacle area is in a direction opposite that of the target. We expect to present our preliminary results on this work at a relevant conference, and to complete a full-length publication describing this work sometime in 1995.

4. Neural Networks for Learning a Body-Centered Representation of 3-D Target Position

This work, to appear in the *Journal of Cognitive Neuroscience*, represents the third article in a series aimed at modeling how the brain autonomously learns spatial representations capable of controlling flexible goal-oriented movements. In it, Grossberg and Guenther, working with Dan Bullock and Doug Greve, designed a neural network to model how the brain may autonomously learn a body-centered representation of 3-D target position by combining information about retinal target position, eye position, and head position in real time. Such a body-centered spatial representation enables accurate movement commands to the limbs to be generated despite changes in the spatial relationships between the eyes, head,

body, and limbs through time. The representation is a vector representation—otherwise known as a parcellated distributed representation—of target vergence with respect to the two eyes, and of the horizontal and vertical spherical angles of the target with respect to a cyclopean egocenter. A similar representation has been reported in the caudal midbrain and medulla of the frog, as well as in psychophysical movement studies in humans. A head-centered vector representation of this type is generated by two stages of opponent processing that combine corollary discharges of outflow movement signals to the two eyes. This head-centered vector representation interacts with representations of neck movement commands to generate a body-centered estimate of target position. The contributions of the neck command signals to this vector representation are learned during head movements made while the gaze remains fixed on a foveated target. An initial estimate is stored and offset of a gating signal prevents the stored estimate from being reset during a gaze-maintaining head movement. As the head moves, new estimates are generated and compared with the stored estimate. If the estimates are unequal, the comparison generates non-zero difference vectors, which act as error signals to drive the learning process.

5. 3-D Vision and Figure-Ground Separation by Visual Cortex

In this work, which appeared this year in *Perception and Psychophysics*, Grossberg further developed a neural network theory of 3-D vision, called FACADE Theory. The theory proposes a solution of the classical figure-ground problem for biological vision. It does so by suggesting how boundary representations and surface representations are formed within a Boundary Contour System (BCS) and a Feature Contour System (FCS). The BCS and FCS interact reciprocally to form 3-D boundary and surface representations that are mutually consistent. Their interactions generate 3-D percepts wherein occluding and occluded object parts are separated, completed, and grouped. The theory clarifies how preattentive processes of 3-D perception and figure-ground separation interact reciprocally with attentive processes of spatial localization, object recognition, and visual search. A new theory of stereopsis is proposed that predicts how cells sensitive to multiple spatial frequencies, disparities, and orientations are combined by context-sensitive filtering, competition, and cooperation to form coherent BCS boundary segmentations. Several factors contribute to figure-ground pop-out, including: boundary contrast between spatially contiguous boundaries, whether due to scenic differences in luminance, color, spatial frequency, or disparity; partially ordered interactions from larger spatial scales and disparities to smaller scales and disparities; and surface filling-in restricted to regions surrounded by a connected boundary. Phenomena such as 3-D pop-out from a 2-D picture, DaVinci stereopsis, 3-D neon color spreading, completion of partially occluded objects, and figure-ground reversals are analysed. The BCS and FCS subsystems model aspects of how the two parvocellular cortical processing streams that join the Lateral Geniculate Nucleus to prestriate cortical area V4 interact to generate a multiplexed representation of Form-And-Color-And-DEpth, or FACADE, within area V4. Area V4 is suggested to support figure-ground separation and to interact with cortical mechanisms of spatial attention, attentive object learning, and visual search. Adaptive Resonance Theory (ART) mechanisms model aspects of how prestriate visual cortex interacts reciprocally with a visual object recognition system in inferotemporal cortex (IT) for purposes of attentive object learning and categorization. Object attention mechanisms of the What cortical processing stream through IT cortex are distinguished from spatial attention mechanisms of the Where cortical processing stream through parietal cortex. Parvocellular BCS and FCS signals interact with the model What steam. Parvocellular FCS and magnocellular Motion BCS signals interact with the model Where stream. Reciprocal interactions between these visual, What, and Where mechanisms are used to discuss data about visual search and saccadic eye movements, including fast search of conjunctive targets, search of 3-D surfaces, selective search of like-colored targets, attentive tracking of multi-element groupings, and recursive search of simultaneously presented targets. These interactions shed new light on how spatial and recognition mechanisms interact to identify targets moving in space.

6. A Neural Theory of Attentive Visual Search: Interactions of Visual, Spatial, and Object Representations

Visual search by humans for targets distributed in space among distractors is remarkably efficient. In this work, which appeared this year in *Psychological Review*, Grossberg, Mingolla, and Ross show how visual search data can be given a unified quantitative explanation by a model of how spatial maps in the parietal cortex and object recognition categories in the inferotemporal cortex deploy attentional resources as they reciprocally interact with visual representations in the prestriate cortex. The model visual representations are organized into multiple boundary and surface representations. Visual search in the model is initiated by organizing multiple items that lie within a given boundary or surface representation into a candidate search grouping. These items are matched with object recognition categories to test for matches or mismatches. Mismatches can trigger deeper searches and recursive selection of new groupings until a target object is identified. This search model is algorithmically specified to quantitatively simulate search data using a single set of parameters, as well as to qualitatively explain a still larger data base, including data of Aks and Enns (1992), Bravo and Blake (1990), Egeth, Virzi, and Garbart (1984), Cohen and Ivry (1991), Enns and Rensink (1990), He and Nakayama (1992), Humphreys, Quinlan, and Riddoch (1989), Mordkoff, Yantis, and Egeth (1990), Nakayama and Silverman (1986), Treisman and Gelade (1980), Treisman and Sato (1990), Wolfe, Cave, and Franzel (1989), and Wolfe and Friedman-Hill (1992). The model hereby provides an alternative to recent variations on the Feature Integration and Guided Search models, and grounds the analysis of visual search in neural models of preattentive vision, attentive object learning and categorization, and attentive spatial localization and orientation.

7. The What-and-Where Filter: A Spatial Mapping Neural Network for Object Recognition and Image Understanding

In this work, Carpenter, Grossberg, and Greg Lesher have modeled a What-and-Where filter that forms part of a neural network architecture for spatial mapping, object recognition, and image understanding. The Where filter responds to an image figure that has been separated from its background. It generates a spatial map whose cell activations simultaneously represent the position, orientation, and size of the figure (where it is). This spatial map may be used to direct spatially localized attention to these image features. A multiscale array of oriented detectors, followed by competitive interactions between position, orientation, and size scales, is used to define the Where filter. The Where filter may be used to transform the image figure into an invariant representation that is insensitive to the figure's original position, orientation, and size. This invariant figural representation forms part of a system devoted to attentive object learning and recognition (what it is). The Where spatial map of all the figures in an image, taken together with the invariant recognition categories that identify these figures, can be used to learn multidimensional representations of objects and their spatial relationships for purposes of image understanding. The What-and-Where filter is inspired by neurobiological data showing that a Where processing stream in the cerebral cortex is used for attentive spatial localization and orientation, whereas a What processing stream is used for attentive object learning and recognition.

8. A Collection of ART-Family Graphical Simulators

The Adaptive Resonance Theory (ART) architecture, first proposed by Grossberg, is a self-organizing neural network for stable pattern categorization in response to arbitrary input sequences. Since its original formulation, several versions of ART have been proposed, each designed to handle a particular task or input format. Recent ART architectures have been developed by Carpenter and Grossberg working with CNS graduate students. Some of these models have been designed to work in a supervised fashion, offering a viable alternative to supervised neural networks such as backpropagation. Perhaps the best-known variant of

ART is ART 2, an unsupervised neural network that handles analog inputs. In collaboration with a graduate student, Professor Gaudiano has developed a series of simulators for some of the ART-family neural architectures, namely, ART 2, ART2-A, Fuzzy ART, and Fuzzy ARTMAP. These simulators, which will soon become available on the public domain, are written in C++ and utilize the Tcl/Tk language for the graphical user interface. The software was implemented on UNIX and NeXT workstations, and should be easily ported to other platforms. It is expected that this software package will be utilized extensively both as a pedagogical tool and as a tool for research around the world.

SELECTED ABSTRACTS

CEREBELLAR LEARNING IN AN OPPONENT MOTOR CONTROLLER FOR ADAPTIVE LOAD COMPENSATION AND SYNERGY FORMATION

Daniel Bullock†, José L. Contreras-Vidal‡, and Stephen Grossberg§

Technical Report CAS/CNS-TR-93-009
Boston, MA: Boston University
In **Proceedings of the World Congress on Neural Networks**
Hillsdale, NJ: Erlbaum Associates, 1993, **IV**, 481–486

Abstract

This paper shows how a minimal neural network model of the cerebellum may be embedded within a sensory-neuro-muscular control system that mimics known anatomy and physiology. With this embedding, cerebellar learning promotes load compensation while also allowing both coactivation and reciprocal inhibition of sets of antagonist muscles. In particular, we show how synaptic long term depression guided by feedback from muscle stretch receptors can lead to trans-cerebellar gain changes that are load-compensating. It is argued that the same processes help to adaptively discover multi-joint synergies. Simulations of rapid single joint rotations under load illustrates design feasibility and stability.

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A SELF-ORGANIZING NEURAL NETWORK FOR LEARNING A BODY-CENTERED INVARIANT REPRESENTATION OF 3-D TARGET POSITION

Daniel Bullock, Douglas Greve, Stephen Grossberg, and Frank H. Guenther

Technical Report CAS/CNS-TR-93-010
Boston, MA: Boston University
In **Proceedings of the World Congress on Neural Networks**
Hillsdale, NJ: Erlbaum Associates, 1993, **I**, 405–408

Abstract

This paper describes a self-organizing neural network that rapidly learns a body-centered representation of 3-D target positions. This representation remains invariant under head and eye movements, and is a key component of sensory-motor systems for producing motor equivalent reaches to targets (Bullock, Grossberg, and Guenther, 1993).

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A SELF-ORGANIZING NEURAL MODEL OF MOTOR EQUIVALENT REACHING AND TOOL USE BY A MULTIJOINT ARM

Daniel Bullock†, Stephen Grossberg†, and Frank H. Guenther‡

Journal of Cognitive Neuroscience, 1993, **5**, 408–435

Abstract

This paper describes a self-organizing neural model for eye-hand coordination. Called the DIRECT model, it embodies a solution of the classical motor equivalence problem. Motor equivalence computations allow humans and other animals to flexibly employ an arm with more degrees of freedom than the space in which it moves to carry out spatially defined tasks under conditions that may require novel joint configurations. During a motor babbling phase, the model endogenously generates movement commands that activate the correlated visual, spatial, and motor information that are used to learn its internal coordinate transformations. After learning occurs, the model is capable of controlling reaching movements of the arm to prescribed spatial targets using many different combinations of joints. When allowed visual feedback, the model can automatically perform, without additional learning, reaches with tools of variable lengths, with clamped joints, with distortions of visual input by a prism, and with unexpected perturbations. These compensatory computations occur within a single accurate reaching movement. No corrective movements are needed. Blind reaches using internal feedback have also been simulated. The model achieves its competence by transforming visual information about target position and end effector position in 3-D space into a body-centered spatial representation of the direction in 3-D space that the end effector must move to contact the target. The spatial direction vector is adaptively transformed into a motor direction vector, which represents the joint rotations that move the end effector in the desired spatial direction from the present arm configuration. Properties of the model are compared with psychophysical data on human reaching movements, neurophysiological data on the tuning curves of neurons in the monkey motor cortex, and alternative models of movement control.

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A NEURAL NETWORK MODEL FOR CURSIVE SCRIPT PRODUCTION

Daniel Bullock†, Stephen Grossberg‡, and Christian Mannes§

Technical Report CAS/CNS TR-92-029
Boston, MA: Boston University
Biological Cybernetics, 1993, **70**, 15–28

Abstract

This article describes a neural network model, called the VITEWRITE model, for generating handwriting movements. The model consists of a sequential controller, or motor program, that interacts with a trajectory generator to move a hand with redundant degrees of freedom. The neural trajectory generator is the Vector Integration to Endpoint (VITE) model for synchronous variable-speed control of multijoint movements. VITE properties enable a simple control strategy to generate complex handwritten script if the hand model contains redundant degrees of freedom. The proposed controller launches transient directional commands to independent hand synergies at times when the hand begins to move, or when a velocity peak in a given synergy is achieved. The VITE model translates these temporally disjoint synergy commands into smooth curvilinear trajectories among temporally overlapping synergetic movements. The separate "score" of onset times used in most prior models is hereby replaced by a self-scaling activity-released "motor program" that uses few memory resources, enables each synergy to exhibit a unimodal velocity profile during any stroke, generates letters that are invariant under speed and size rescaling, and enables effortless connection of letter shapes into words. Speed and size rescaling are achieved by scalar GO and GRO signals that express computationally simple volitional commands. Psychophysical data concerning hand movements, such as the isochrony principle, asymmetric velocity profiles, and the two-thirds power law relating movement curvature and velocity arise as emergent properties of model interactions.

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MOTIVATION

Clark Dorman† and Paolo Gaudiano‡

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Boston, MA: Boston Universityy
To appear in M. Arbib (Ed.)
Handbook of Brain Theory and Neural Networks
Cambridge, MA: MIT Press, in press, 1994

Abstract

The ability of humans and animals to survive in a constantly changing environment is a testament to the power of biological processes. At any moment in our lives, we are faced with many sensory stimuli, and we can typically generate a large number of behaviors. How do we learn to ignore irrelevant information and suppress inappropriate behavior so that we may function in a complex environment?

In this chapter we discuss *motivation*, the internal force that produces actions on the basis of the momentary balance between our needs and the demands of our environment. We first give a description of motivation and how it is studied, focusing on behavioral and physiological studies. We then discuss the role of motivation in behavioral theories and neural network modeling.

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AN UNSUPERVISED ERROR-BASED NEURAL NETWORK MODEL FOR THE GENERATION AND CONTROL OF MOVEMENT TRAJECTORIES

Paolo Gaudiano†

In **Proceedings of the AAAS Science Innovation Conference**
August 6–10, 1993, Boston, Massachusetts, **93-21S**, 108–109

Abstract

How can humans and animals be able to carry out novel motor tasks that they have never learned before? How is perceptual information about their environment transformed into spatial representations that can be used to generate accurate motor commands? In this talk I will present the Vector Associative Map (VAM), a self-organizing, unsupervised neural network model that has been applied to a variety of problems in the adaptive control of movemente trajectories. The VAM was derived from the Vector Integration To Endpoint (VITE) model (Bullock & Grossberg, 1988, *Psych. Rev.*. **95**, 49) for the generation and control of movement trajectories. The VAM model has been applied to a variety of learning tasks, including intramodal calibration of arm control parameters, intermodal learning of spatial-to-motor maps (Gaudiano & Grossberg, 1991, *Neural Networks*. **4**, 147), and learning an invariant representation of 3-D target positions in head-centered coordinates (Guenther, Bullock, Greve, Grossberg, *J. Cog. Neurosci.*. in press). The VAM model advances our understanding of brain function in the realm of adaptive motor control, and it holds great potential for practical applications in robotics and control.

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A NONLINEAR MODEL OF SPATIOTEMPORAL RETINAL PROCESSING: SIMULATIONS OF X AND Y RETINAL GANGLION CELL BEHAVIOR

Paolo Gaudiano†

Technical Report CAS/CNS-TR-93-048
Boston, MA: Boston University
Vision Research, 1994, **34**, 1767–1784

Abstract

This article introduces a nonlinear model of neural processing in the vertebrate retina, comprising model photoreceptors, model push-pull bipolar cells, and model ganglion cells. Analyses and simulations show that the model can account for several aspects of both X and Y cat retinal ganglion cell behavior. In particular, with a choice of parameters that mimics *beta* cells, the model exhibits X-like linear spatial summation (null response to contrast-reversed gratings) in spite of photoreceptor nonlinearities; on the other hand, a choice of parameters that mimics *alpha* cells leads to Y-like frequency doubling. These and other results suggest that X and Y cells can be seen as variants of a single neural circuit. The model also suggests that both depolarizing and hyperpolarizing bipolar cells converge onto both ON and OFF ganglion cell types, although the effects of this push-pull convergence can be elusive when recording from individual ganglion cells. These hypotheses are supported in the article by a number of computer simulation results.

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THE NEURAL DYNAMICS APPROACH TO SENSORY-MOTOR CONTROL: OVERVIEW AND RECENT APPLICATIONS IN MOBILE ROBOT CONTROL AND SPEECH PRODUCTION

Paolo Gaudiano†, Frank H. Guenther‡, and Eduardo Zalama

Invited article to appear in **Progress in Neural Networks**

Abstract

This chapter discusses a collection of models that utilize adaptive and dynamical properties of neural networks to solve problems of sensory-motor control for biological organisms and robots. The chapter begins with an overview of several unsupervised neural network models developed at the Center for Adaptive Systems during the past decade. These models have been used to explain a variety of data in research areas ranging from the cortical control of eye and arm movements to spinal regulation of muscle length and tension. Next, two recent models that build on important concepts from this earlier work are presented. The first of these models is an adaptive neural network controller for a visually-guided mobile robot. The neural network controller enables the robot to move to arbitrary targets without any knowledge of the robot's kinematics, immediately and automatically compensating for perturbations such as target movements, wheel slippage, or changes in the robot's plants. The controller also adapts to long-term perturbations, enabling the robot to compensate for statistically significant changes in its plant. The second model is a self-organizing neural network addressing speech motor skill acquisition and speech production. This model explains a wide range of data on contextual variability, motor equivalence, coarticulation, and speaking rate effects. Model parameters are learned during a babbling phase, using only information available to a babbling infant. After learning, the model can produce arbitrary phoneme strings, again exhibiting automatic compensation for perturbations or constraints on the articulators. Finally, other recent models using a neural dynamics approach are summarized and future research avenues are outlined.

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A NEURAL NETWORK MODEL OF DYNAMIC RECEPTIVE FIELD REORGANIZATION

P. Gaudiano, S. Olson, D. Tal, and B. Fischl

Society for Neuroscience Abstracts, 1993, **19**, #328.19

Abstract

Primary sensory cortex is traditionally viewed as a passive filter, extracting information for processing in higher cortical centers. However, recent experiments have revealed a remarkable degree of plasticity in primary sensory cortex, particularly in visual cortex (Gilbert, 1992; Heinen & Skavenski, 1991; Kaas *et al.*, 1991) and somatosensory cortex (Merzenich *et al.*, 1984; Pons *et al.*, 1991; Ramachandran *et al.*, 1992). Receptive fields of cells in visual cortex have been shown to respond dynamically to changes in the visual environment, both within and outside the cells' classically defined receptive fields. This reorganization occurs on a variety of time scales, from seconds to years (Gilbert, 1992). We show a simple neural network model based on Adaptive Resonance Theory (ART: Carpenter & Grossberg, 1987; Grossberg, 1976) that displays some of the dynamical reorganization found in visual and somatosensory cortex. According to ART, plasticity is maintained throughout life, although feedback interactions prevent spurious reorganization during normal cortical function. In qualitative agreement with experimental results, simulated cortical cell receptive fields expand and contract as a result of attentional influences, real and artificial retinal lesions (both immediate and long-term reorganization), and preferential stimulation. Information from outside a cell's receptive field directly and indirectly mediates the cell's response. Both the rapid and long-term receptive field reorganizations arise as a consequence of nonlinear network-level interactions that are not fully explicable by examining the responses of individual neurons.

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AN UNSUPERVISED NEURAL NETWORK FOR REAL-TIME LOW-LEVEL CONTROL OF A MOBILE ROBOT: NOISE RESISTANCE, STABILITY, AND HARDWARE IMPLEMENTATION

Paolo Gaudiano†, Eduardo Zalama, and Juan López Coronado

Technical Report CAS/CNS-TR-94-019
Boston, MA: Boston University
IEEE Transactions on Systems, Man, and Cybernetics, in press, 1994

Abstract

We have recently introduced a neural network mobile robot controller (NETMORC). The controller is based on earlier neural network models of biological sensory-motor control. We have shown that NETMORC is able to guide a differential drive mobile robot to an arbitrary stationary or moving target while compensating for noise and other forms of disturbance, such as wheel slippage or changes in the robot's plant. Furthermore, NETMORC is able to adapt in response to long-term changes in the robot's plant, such as a change in the radius of the wheels. In this article we first review the NETMORC architecture, and then we prove that NETMORC is asymptotically stable. After presenting a series of simulations results showing robustness to disturbances, we compare NETMORC performance on a trajectory-following task with the performance of an alternative controller. Finally, we describe preliminary results on the hardware implementation of NETMORC with the mobile robot *ROBUTER*.

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BOUNDARY, BRIGHTNESS, AND DEPTH INTERACTIONS DURING PREATTENTIVE REPRESENTATION AND ATTENTIVE RECOGNITION OF FIGURE AND GROUND

Stephen Grossberg†

Technical Report CAS/CNS-TR-93-003
Boston, MA: Boston University
Italian Journal of Psychology, 1993, **XX**, 771–804

Abstract

This article applies a recent theory of 3-D biological vision, called FACADE Theory, to explain several percepts which Kanizsa pioneered. These include 3-D pop-out of an occluding form in front of an occluded form, leading to completion and recognition of the occluded form; 3-D transparent and opaque percepts of Kanizsa squares, with and without Varin wedges; and interactions between percepts of illusory contours, brightness, and depth in response to 2-D Kanizsa images. These explanations clarify how a partially occluded object representation can be completed for purposes of object recognition, without the completed part of the representation necessarily being seen. The theory traces these percepts to neural mechanisms that compensate for measurement uncertainty and complementarity at individual cortical processing stages by using parallel and hierarchical interactions among several cortical processing stages. These interactions are modelled by a Boundary Contour System (BCS) that generates emergent boundary segmentations and a complementary Feature Contour System (FCS) that fills-in surface representations of brightness, color, and depth. The BCS and FCS interact reciprocally with an Object Recognition System (ORS) that binds BCS boundary and FCS surface representations into attentive object representations. The BCS models the parvocellular LGN—Interblob—Interstripe—V4 cortical processing stream, the FCS models the parvocellular LGN—Blob—Thin Stripe—V4 cortical processing stream, and the ORS models inferotemporal cortex.

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SPEECH SOUND ACQUISITION, COARTICULATION, AND RATE EFFECTS IN A NEURAL NETWORK MODEL OF SPEECH PRODUCTION

Frank H. Guenther†

Technical Report CAS/CNS-TR-94-01
Boston, MA: Boston University
Psychological Review, in press, 1994

Abstract

This work describes a neural network model of speech motor skill acquisition and speech production that explains a wide range of data on contextual variability, motor equivalence, coarticulation, and speaking rate effects. Model parameters are learned during a babbling phase. To explain how infants learn phoneme-specific and language-specific limits on acceptable articulatory variability, the learned speech sound targets take the form of multidimensional regions, or convex hulls, in orosensory coordinates. Reduction of target size for better accuracy during slower speech (in the spirit of the speed-accuracy trade-off described by Fitts' law) leads to differential effects for vowels and consonants, as seen in speaking rate experiments that have been previously taken as evidence for separate control processes for the two sound types. An account of anticipatory coarticulation is posited wherein the target for a speech sound is reduced in size based on context to provide a more efficient sequence of articulator movements. This explanation generalizes the well-known look-ahead model of coarticulation to incorporate convex hull targets. Computer simulations verify the model's properties, including linear velocity/distance relationships, motor equivalence, speaking rate effects, and carryover and anticipatory coarticulation.

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A NEURAL NETWORK MODEL OF SPEECH ACQUISITION AND MOTOR EQUIVALENT SPEECH PRODUCTION

Frank H. Guenther†

Technical Report CAS/CNS-TR-93-054
Boston, MA: Boston University
Biological Cybernetics, in press, 1994

Abstract

This article describes a neural network model that addresses the acquisition of speaking skills by infants and subsequent motor equivalent production of speech sounds. The model learns two mappings during a babbling phase. An auditory-to-orosensory mapping specifies a vocal tract target for each speech sound: these targets take the form of convex hulls in orosensory coordinates defining the shape of the vocal tract. The babbling process wherein these convex hull targets are formed explains how an infant can learn phoneme- specific and language-specific limits on acceptable variability of articulator movements. The model also learns an orosensory-to-articulatory mapping wherein cells coding desired movement directions in orosensory space learn articulator movements that achieve these orosensory movement directions. The resulting mapping provides a natural explanation for the formation of coordinative structures. This mapping also makes efficient use of redundancy in the articulator system, thereby providing the model with motor equivalent capabilities. Simulations verify the model's ability to compensate for constraints or perturbations applied to the articulators automatically and without new learning and to explain contextual variability seen in human speech production.

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A COLLECTION OF ART-FAMILY GRAPHICAL SIMULATORS

David Pedini† and Paolo Gaudiano‡

Technical Report CAS/CNS-TR-94-023
Boston, MA: Boston University
Submitted for publication to *Neurocomputing*

Abstract

The Adaptive Resonance Theory (ART) architecture, first proposed by Grossberg (1976a, 1976b), is a self-organizing neural network for stable pattern categorization in response to arbitrary input sequences. Since its original formulation, several versions of ART have been proposed, each designed to handle a particular task or input format. Recent ART architectures have been designed to work in a supervised fashion, offering a viable alternative to supervised neural networks such as backpropagation (Rumelhart, 1986). Perhaps the best-known variant of ART is ART 2 (Carpenter and Grossberg, 1987), an unsupervised neural network that handles analog inputs. We have developed a series of simulators for some of the ART-family neural architectures, namely, ART 2 (Carpenter and Grossberg, 1987), ART2-A (Carpenter, Grossberg, and Rosen, 1991a), Fuzzy ART (Carpenter, Grossberg, and Rosen, 1991b), and Fuzzy ARTMAP (Carpenter, Grossberg, Markuzon, Reynolds, and Rosen, 1992). This article briefly summarizes the history and functionality of ART and its variants, and then describes the software package, which is available in the public domain.

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A REAL-TIME, UNSUPERVISED NEURAL NETWORK MODEL FOR THE CONTROL OF A MOBILE ROBOT IN A NONSTATIONARY ENVIRONMENT

E. Zalama Casanova, Paolo Gaudiano†, and J. Lopéz Coronado

Neural Networks, in press, 1994

Abstract

This article introduces a real-time, unsupervised neural network model that learns to control a two-degree-of-freedom (2-DOF) nonholonomic mobile robot in a nonstationary environment. The model combines associative learning and Vector Associative Map (VAM) learning to generate transformations between spatial and velocity coordinates. The transformations are generated in an initial training phase, during which the robot moves as a result of endogenously generated velocities applied to the robot's wheels. The robot learns the relationship between these small velocities and the resulting incremental movements. During performance, the use of a VAM architecture enables the robot to generalize from the learned incremental movements to reach targets at arbitrary distance and angle from the robot. The VAM structure also enables the robot to perform successfully in spite of drastic changes to the robot's plant, including changes in wheel radius, changes in inter-wheel distance, or changes in the internal time step of the system. This article describes the model, presents illustrative simulation results that include both target and trajectory tracking, and compares the model to other neural network and classical approaches to control.

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